Why wintertime continental temperatures never drop below freezing at 4xCO2

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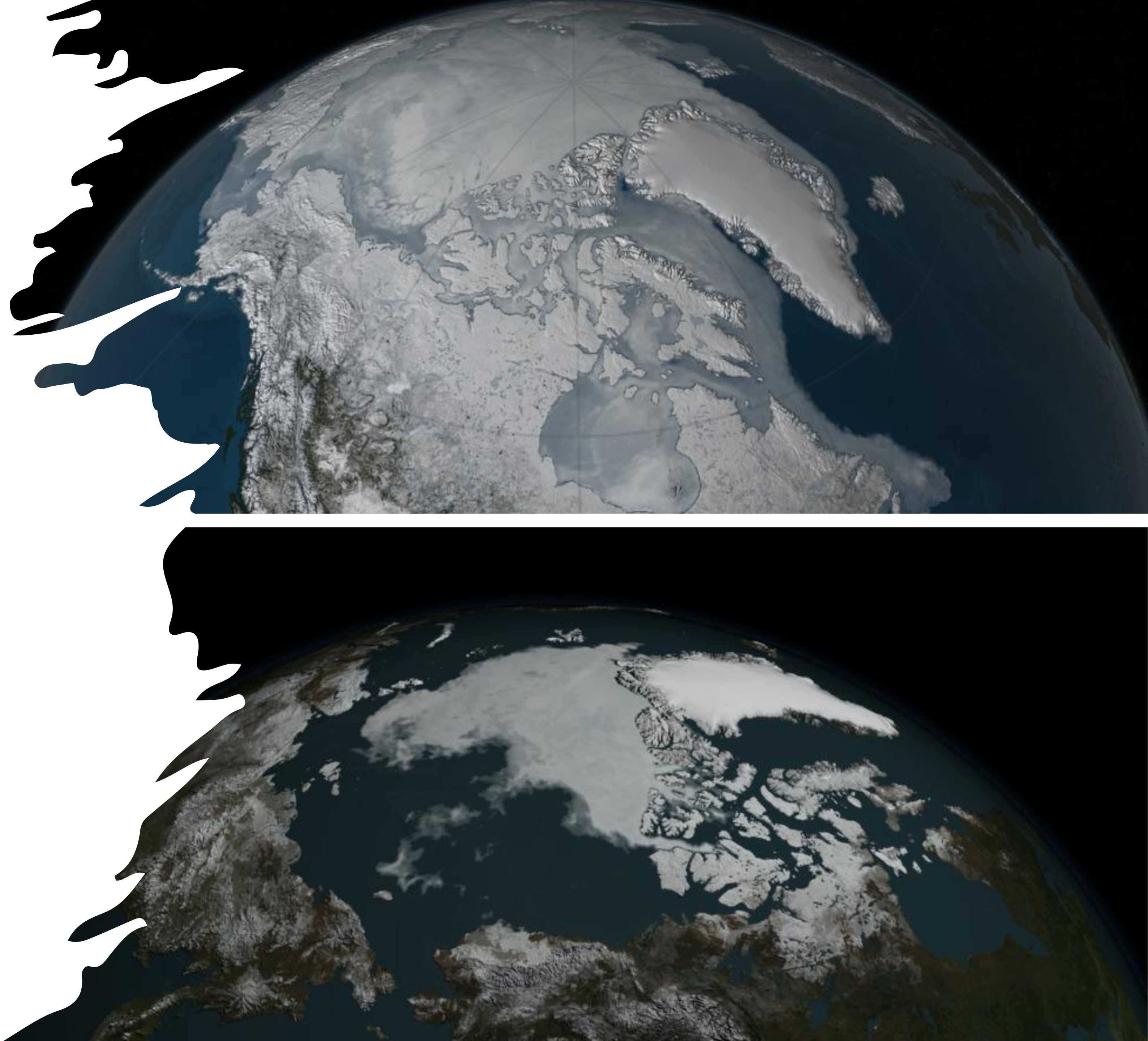

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NASA's Scientific Visualization Studio

The coldest wintertime temperatures are strongly suppressed in warmer climates

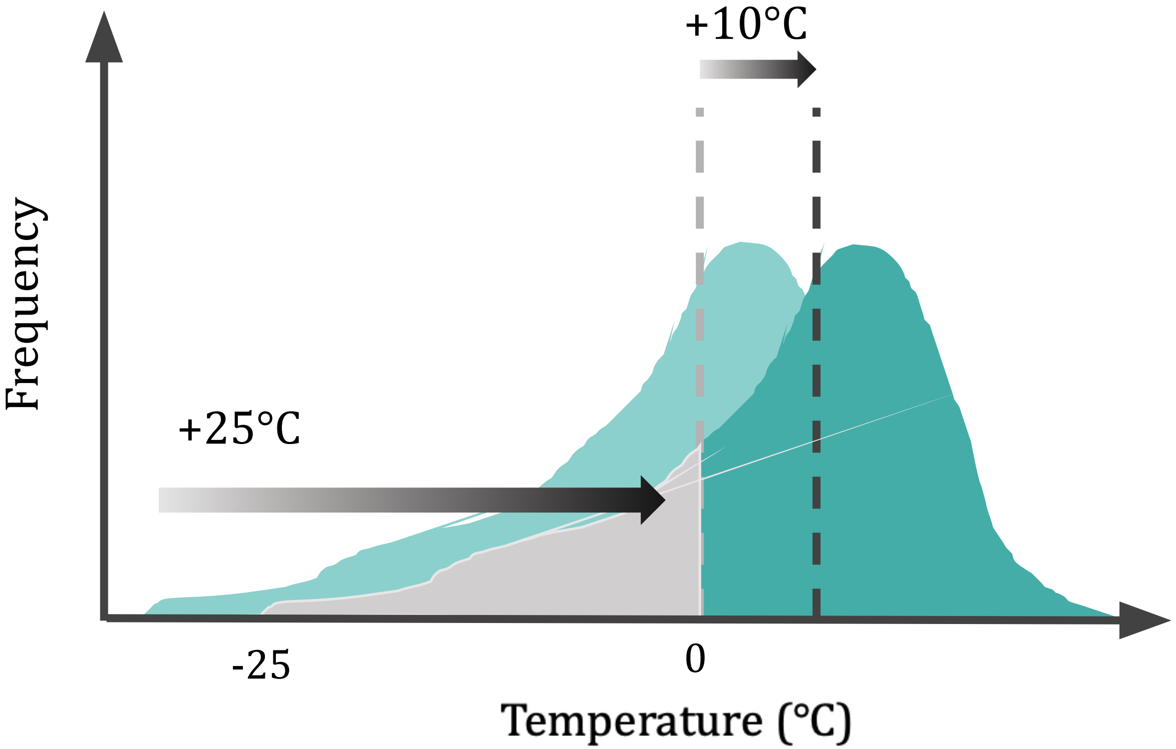
Take the **Eocene** (56-34 mya, >1,000 ppm CO_2) as an example:

Fossils of frost-intolerant species (below) indicate that continental interiors never dropped below freezing, which the mean temperature change alone cannot account for

Crocodile fossil, Eocene-era

Palm frond fossil, Eocene-era

Uniform warming of a modern temperature distribution leaves a **large tail** below freezing that must have been suppressed

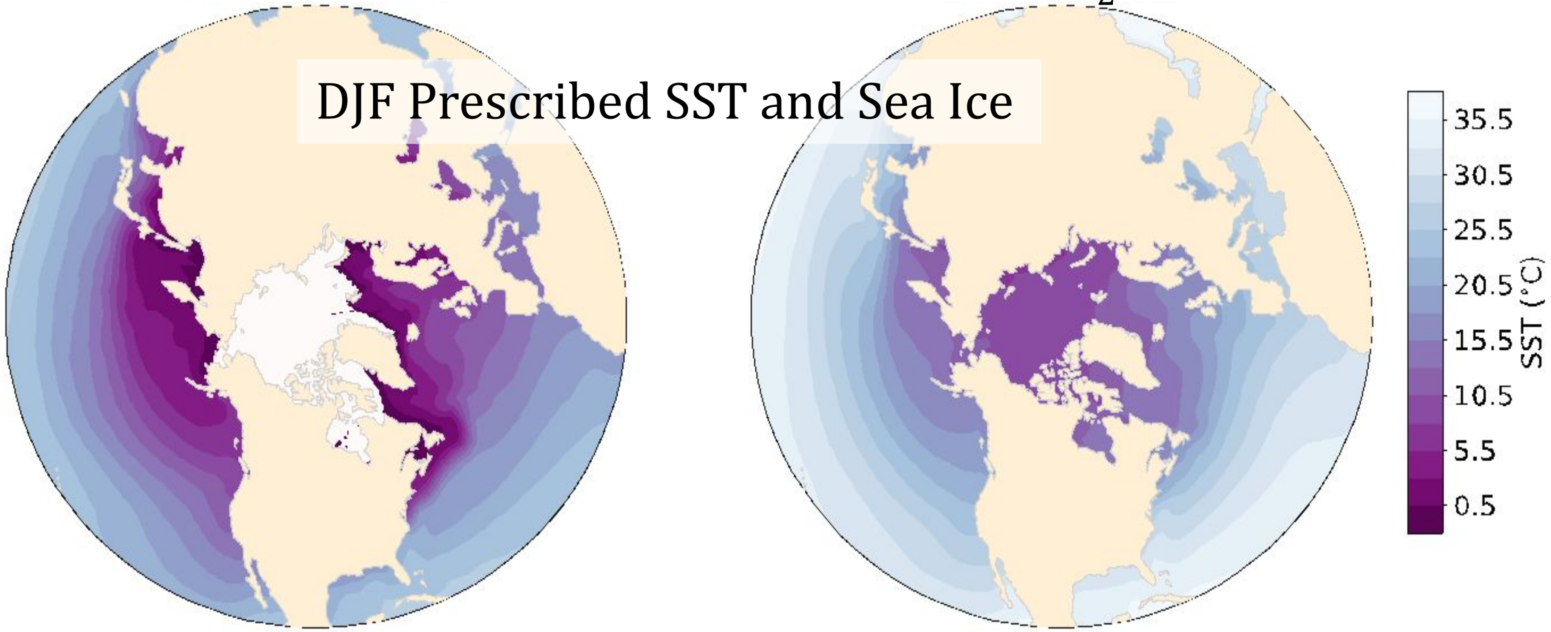


Our method: compare the coldest continental air masses in a pre-industrial vs warmer climate scenario

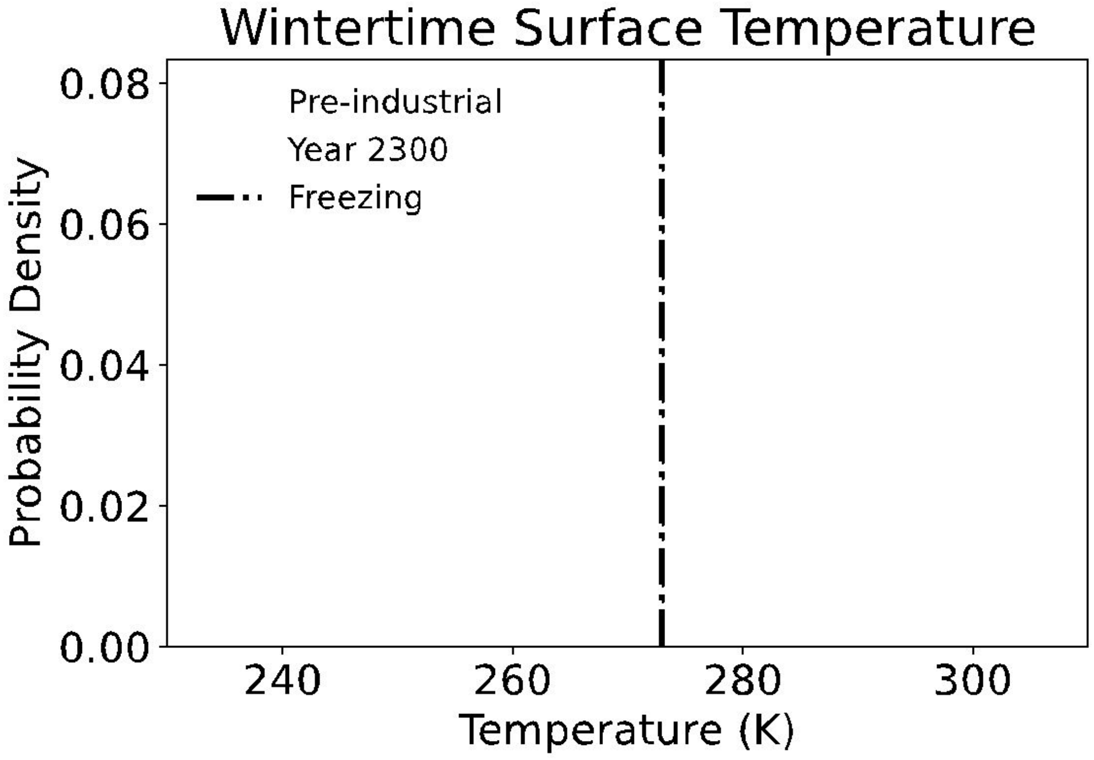
Compare two climate scenarios in CESM2, each run for 50 years:

Pre-industrial case
Start with F2000climo
SST/sea ice from 1850
284.7 ppm CO_2

Year 2300 (~4xCO_2) case
Start with F2000climo
SST/sea ice circa 2300
in extended SSP5-8.5 scenario
2166 ppm CO_2


DJF Prescribed SST and Sea Ice

Temperature distribution both warms and narrows



Simulated temperature distribution (left) has the markers of a more equable climate:

- Significant mean warming: DJF mean temperature increases by 21 ℃
- Coldest air is suppressed: 5th percentile warms by 27 ℃, or 1.3x the mean

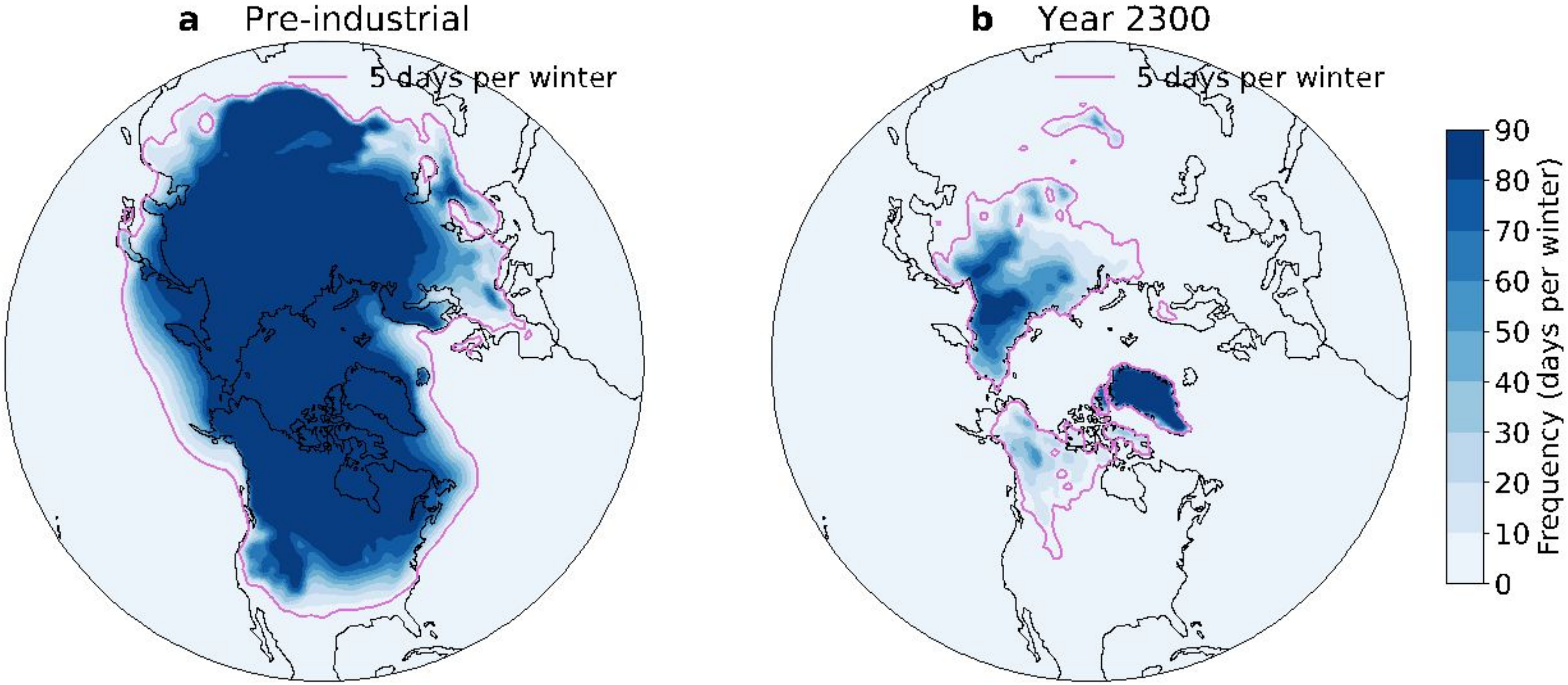
We will think about cold air development in terms of two interrelated factors:

1. **External forcing**: diabatic temperature change from radiation, moisture, clouds, etc
2. **Source regions**: changes to advection and the "initial conditions" of air masses that make their way into North America

Dramatic decrease in availability of below-freezing air at high-latitudes

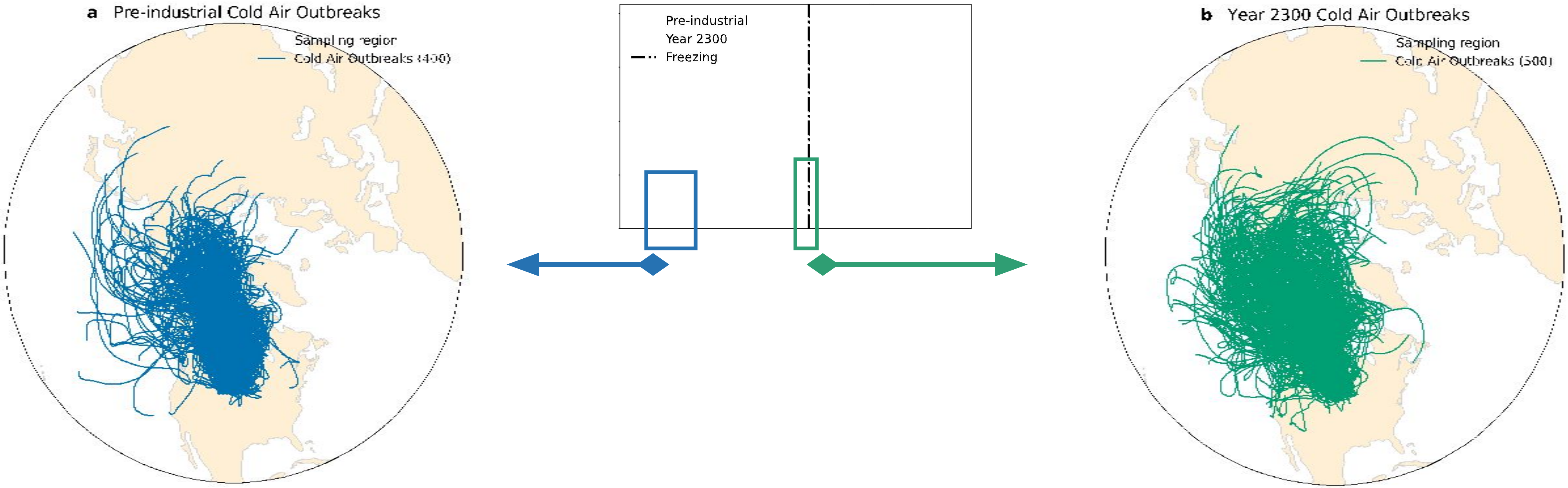
Increased CO_2 and loss of sea ice removes Arctic Ocean as a **source** of below-freezing air and reduces availability on nearby land

Days per year when surface temperature is below freezing

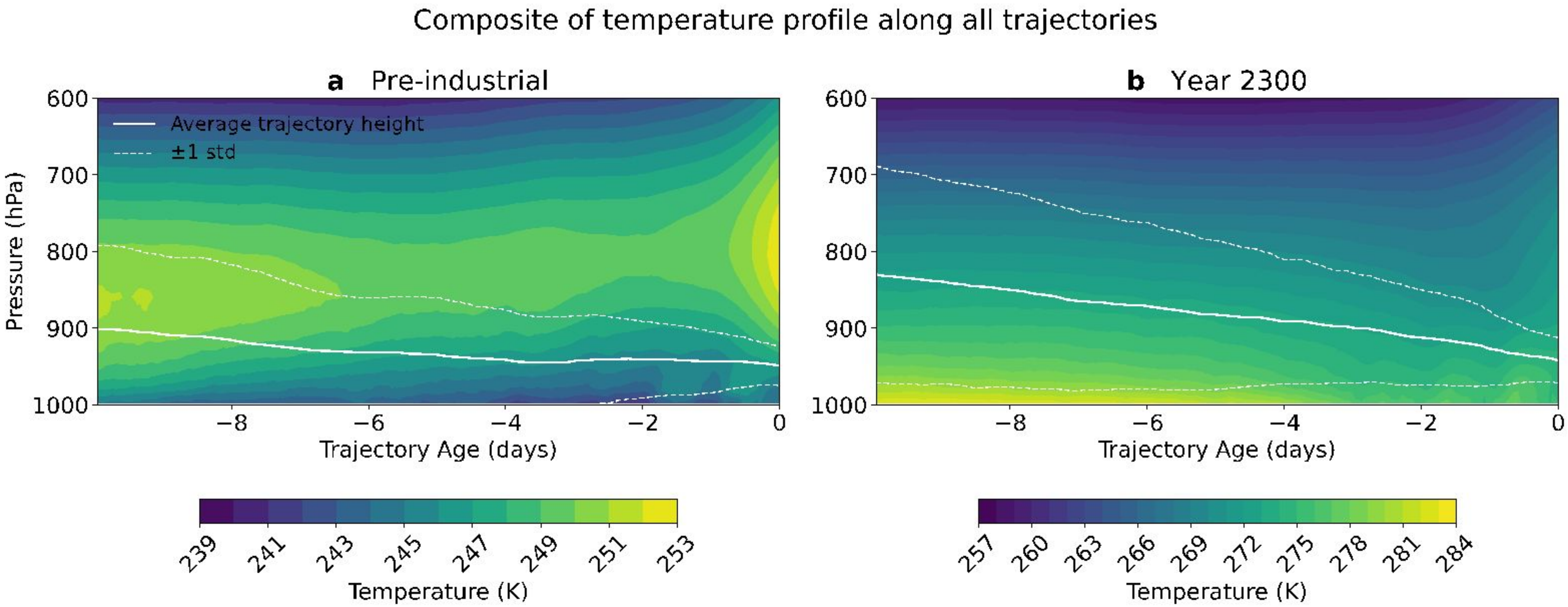


To get at diabatic temperature change, calculate backwards trajectories to study air mass evolution

1. Sample 400-500 events from the coldest 5% of the temperature distribution
2. Calculate a 10-day backwards trajectory for each event (shown below)
3. Look at temperature tendencies from distinct physical processes along each trajectory (next slides)



Near-surface temperature inversion has disappeared in warmer climate

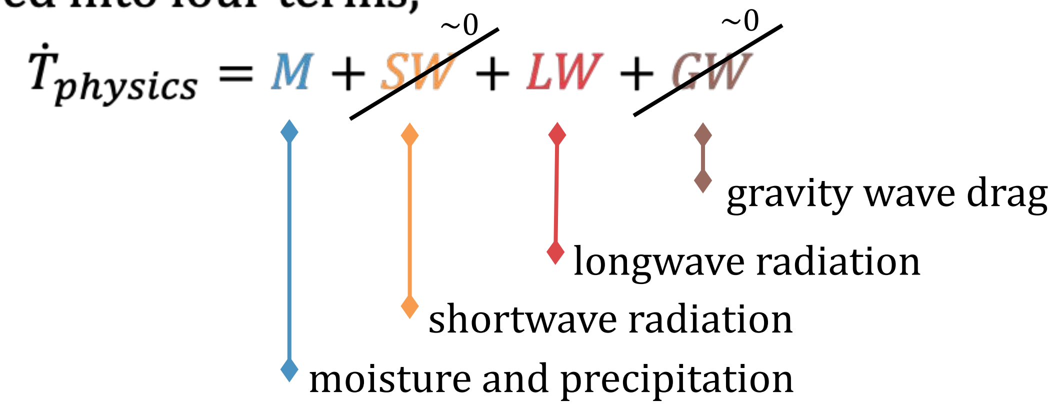


In pre-industrial scenario, temperature increases with height up to ~850 hPa before decreasing again

In warmer climate scenario, temperature strictly decreases with height, so cold air can be sourced from higher altitudes

Diabatic temperature change is a competition between longwave cooling and moist warming

In CAM6, the diabatic temperature tendency can be decomposed into four terms,



$$\dot{T}_{physics} = M + \overset{\sim 0}{\cancel{SW}} + LW + \overset{\sim 0}{\cancel{GW}}$$

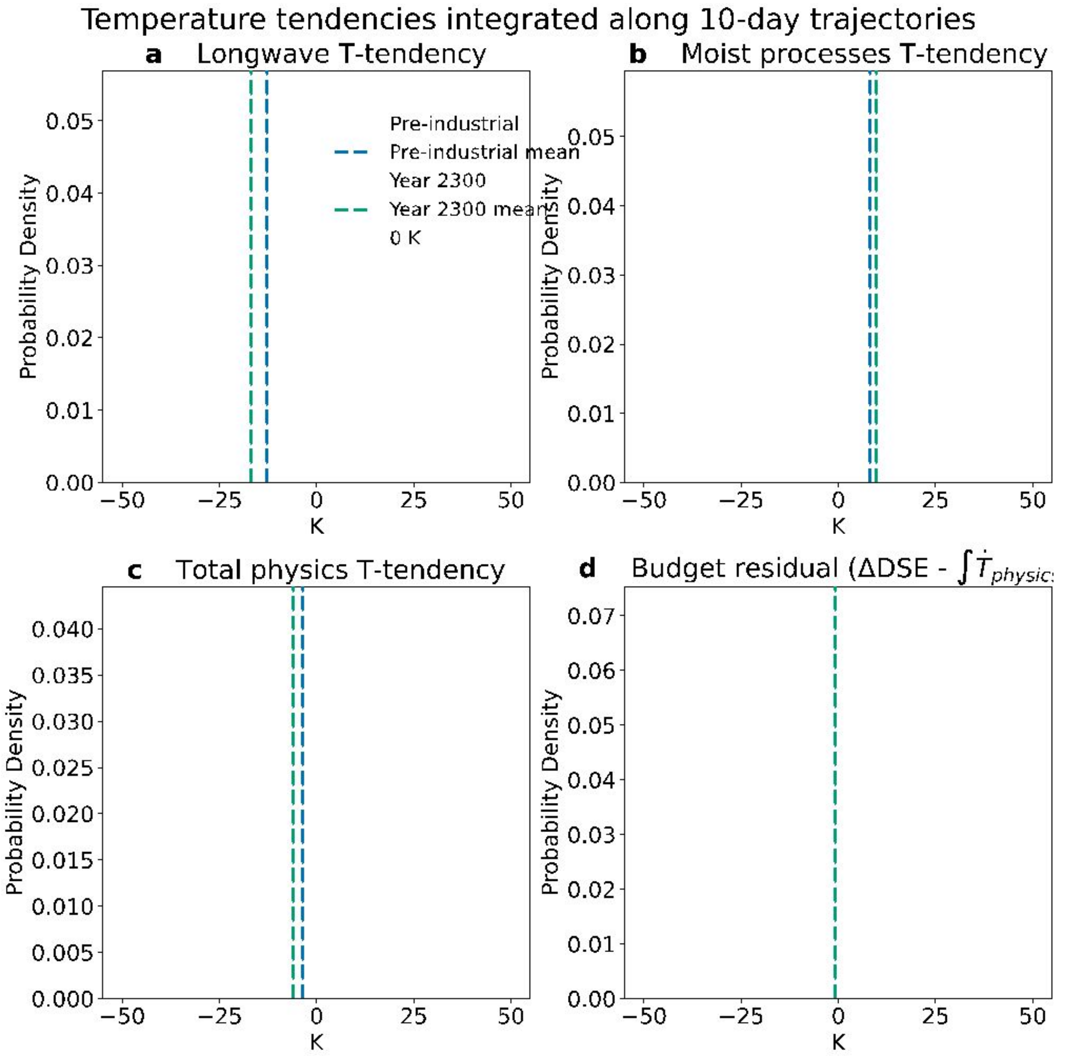
gravity wave drag

longwave radiation

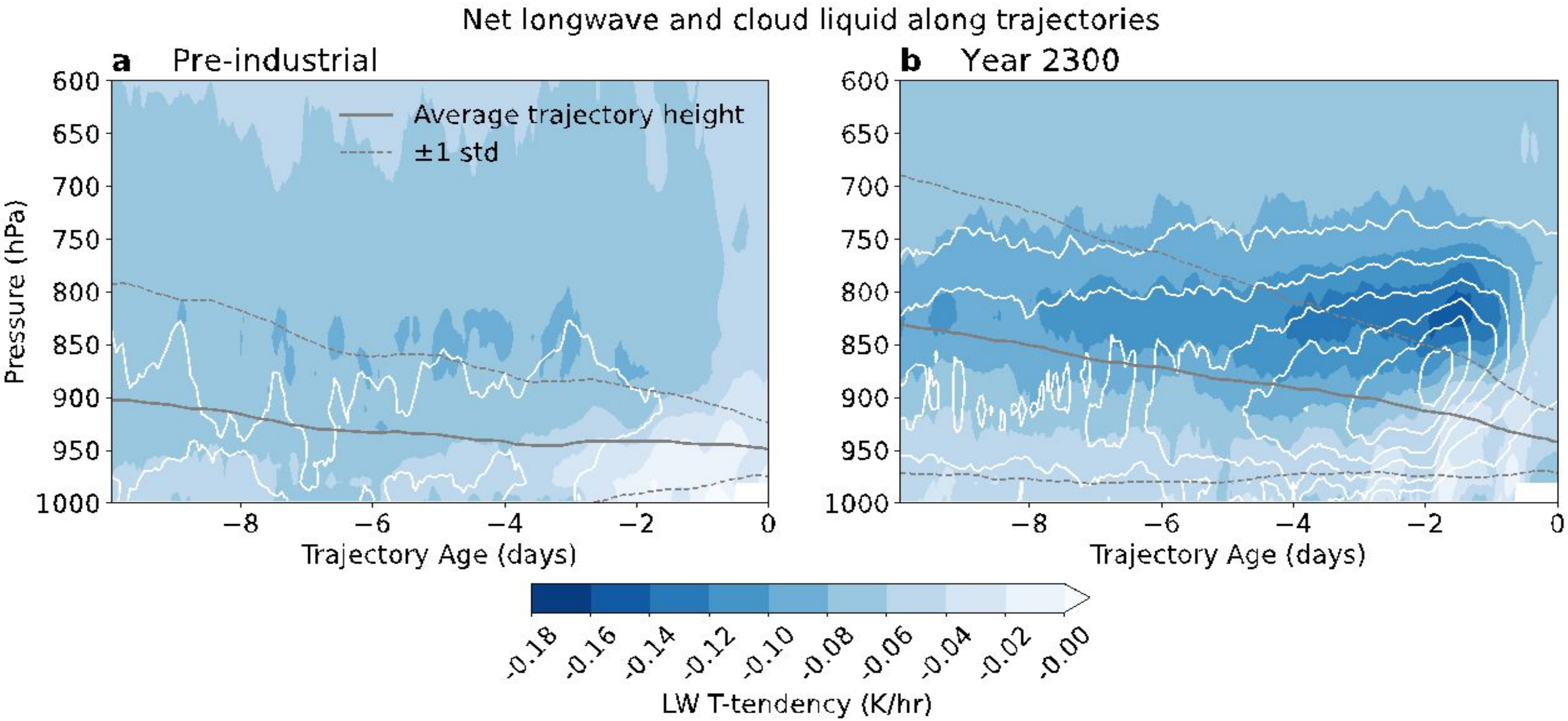
shortwave radiation

moisture and precipitation

Surprisingly similar sources and magnitudes of diabatic temperature change between these two very different climate scenarios. Longwave cooling becomes slightly more intense in the warmer climate scenario (right, a), while moist processes become slightly more variable (right, b).



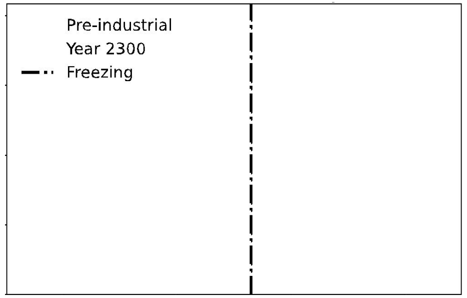
Increase in longwave cooling primarily from cloud-top radiative cooling

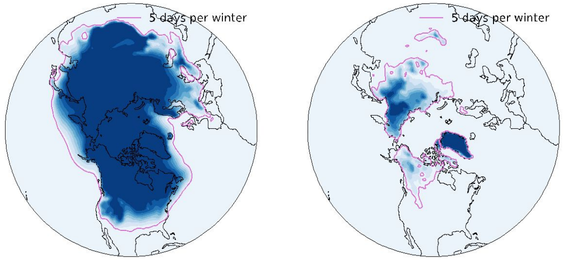


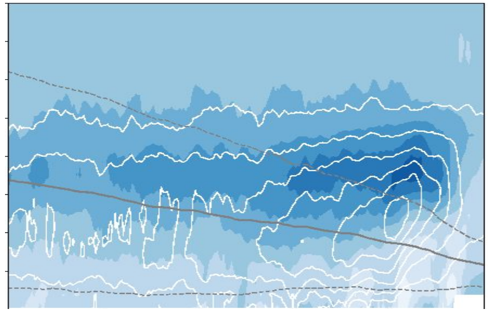
Pre-industrial longwave cooling (shading) is relatively insensitive to height, but there is a clear peak just above the cloud layer (white contours) in the warmer climate

Summary

1. The coldest winter continental air is suppressed relative to the mean in a $4xCO_2$ climate scenario
2. Exposure of the Arctic Ocean surface has dramatically reduced the availability of below-freezing air in high-latitude **source regions**
3. While **diabatic sources** are largely the same between the two climate scenarios, liquid clouds have intensified longwave cooling in the boundary layer in the warmer climate



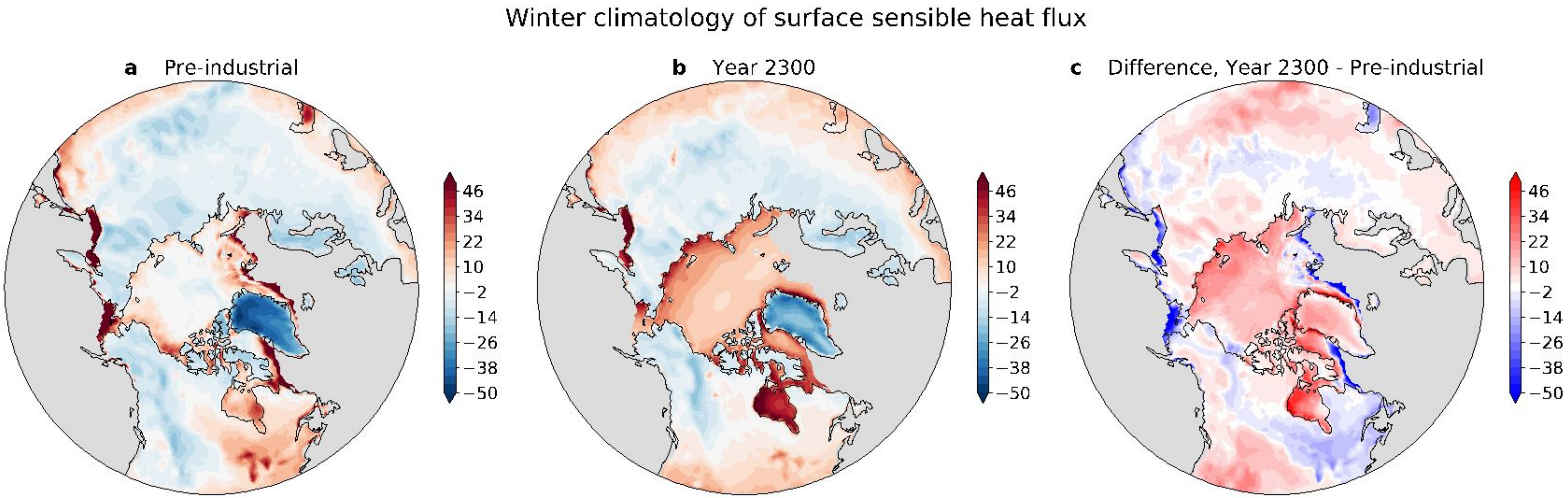




Questions?

Bonus Slides

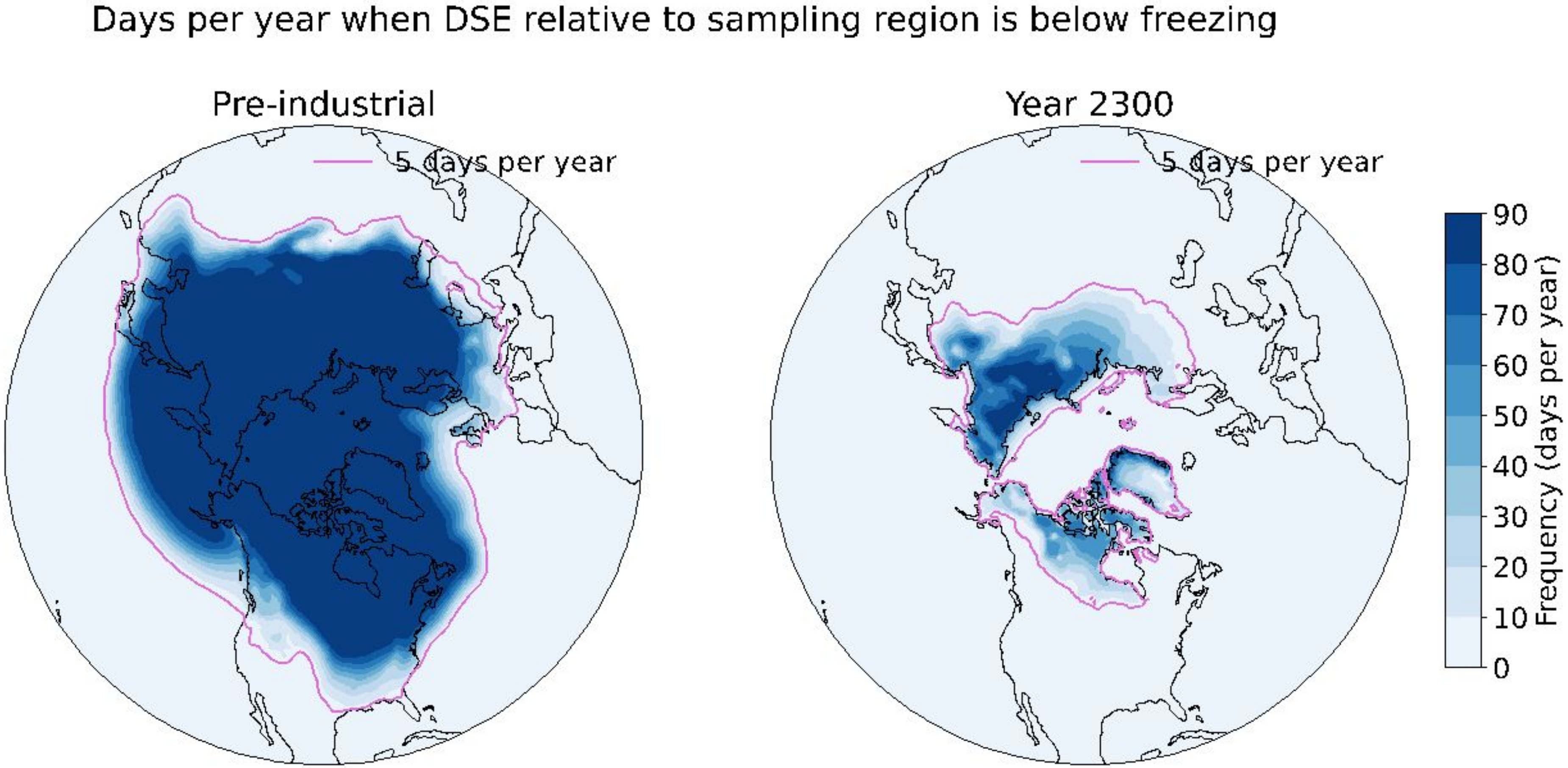
Exposed Arctic Ocean in the warmer climate provides positive heat and moisture fluxes into the atmosphere

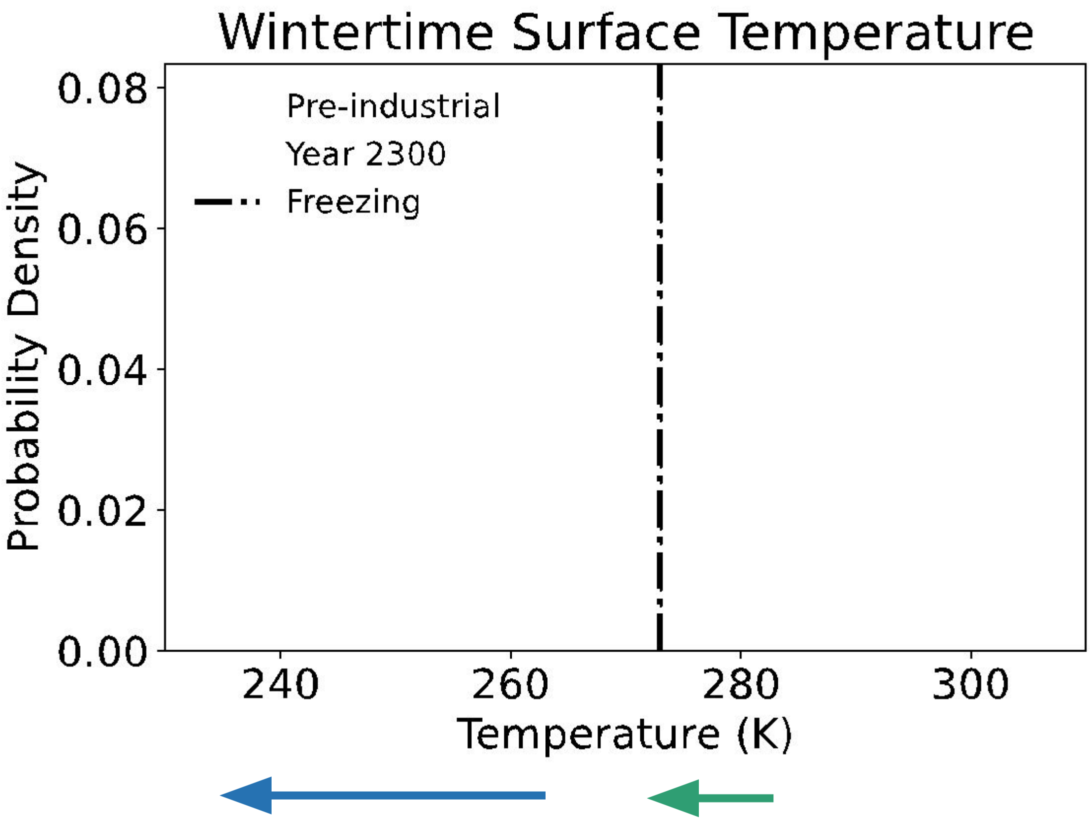


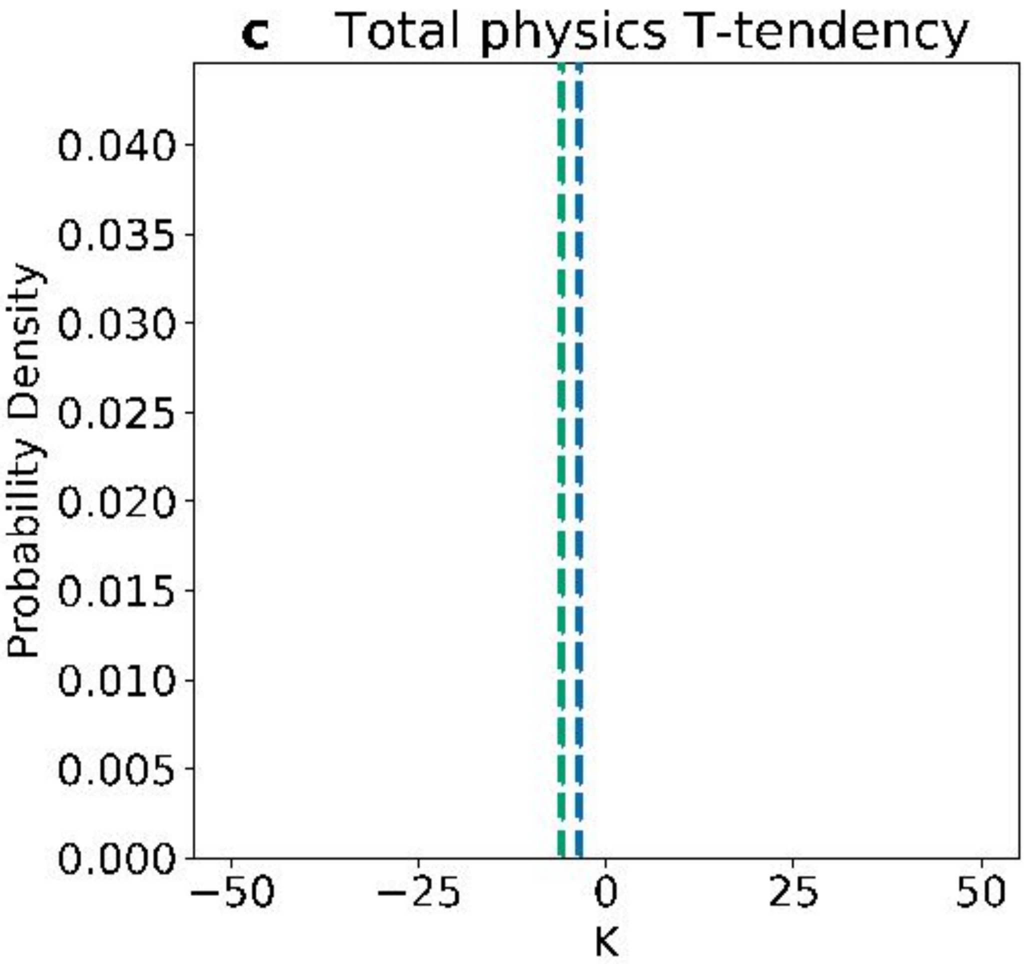
Availability of below-freezing air using adjusted dry static energy:

$$DSE = c_p T + gz$$

where the reference height for z is that of the continental interior (grey box in figure) such that “below freezing” reflects the temperature the air mass would have if lifted/lowered adiabatically to the surface over the continent







20℃ of cooling to get a cold air outbreak

vs

<10℃ of cooling to get a cold air outbreak

~5℃ of cooling *on average*, but many individual trajectories experience 10-20 ℃, which is more than enough to generate (or suppress) a cold air outbreak